# On the application of science systems engineering and uncertainty quantification for ice sheet science and sea level projections

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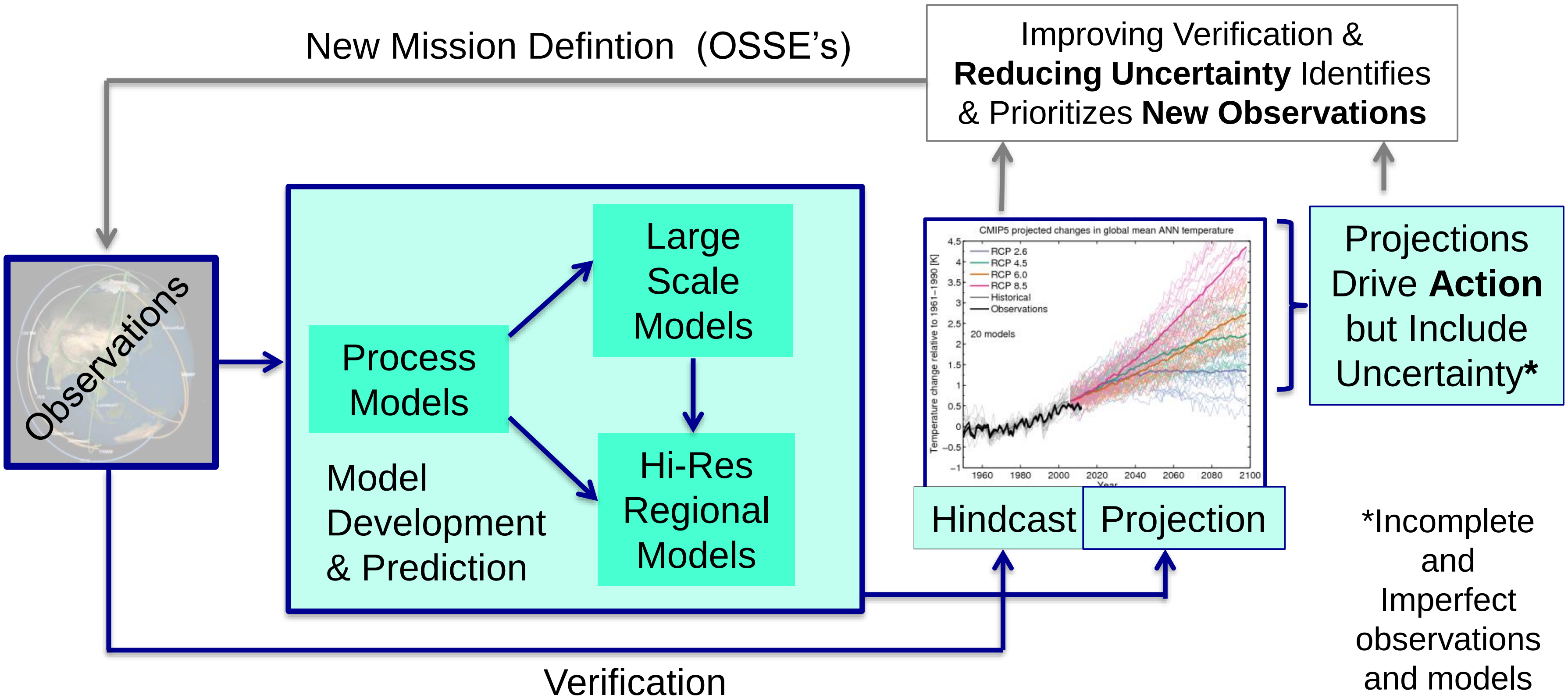
# Motivation

- Two (originally uncoupled) questions:

1. Why can't we do a better job of quantitatively assessing and optimizing new measurements impact on understanding of the climate system?
   - Significant improvement in quantitatively tracing from measurement to instrument design via system engineering approaches
   - Extend to "science system engineering" at higher level of abstraction
2. Why can't we have smaller uncertainties in sea level rise by 2100?
   - Range from ~20 cm to ~200 cm

# JPL Physics based model/prediction/observing optimization framework

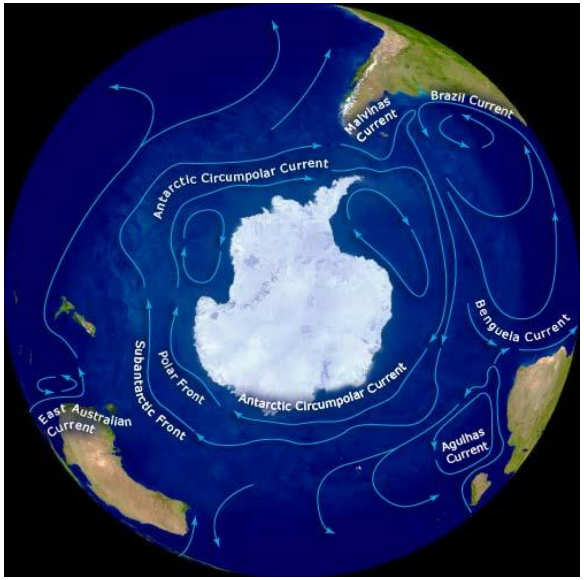



Better quantitative characterization of these complex systems through the application of system engineering and uncertainty quantification methods would enable:

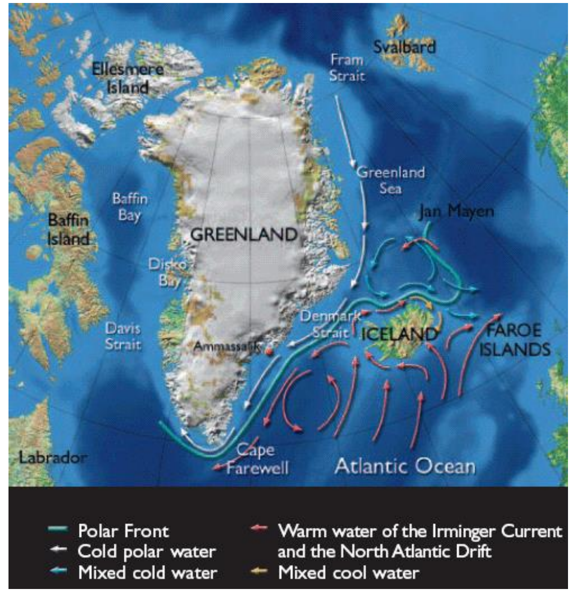
- Improved *science analysis* results
- Improved *science traceability* for optimizing measurement system (mission and instruments) design
- Improved *prioritization* of missions and instruments

# Models

Antarctica




Greenland




**ISSM**

- Ice Sheet System Model
- Adjoint capabilities
- UQ analysis using DAKOTA framework

**ECCO/MITgcm**

- Estimating the Circulation and Climate of the Ocean
- Adjoint capabilities

*Adjoint capability enables easy integration of real or simulated observations for parameter estimation.*

# Multi-step Process

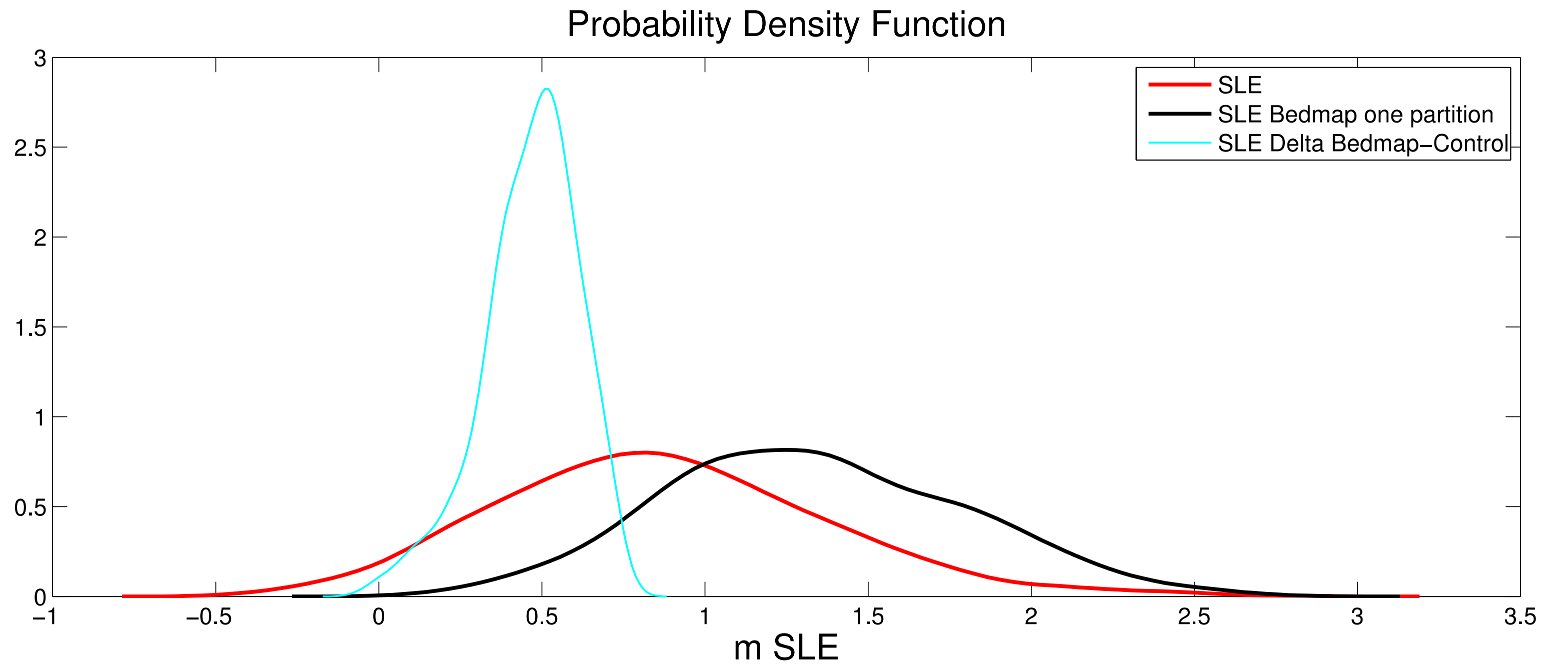
**Parameter values applied as constant values for 100 yr durations**

- Step 1 – single parameter sensitivity experiments
  - Ocean/ice melt rate; viscosity; basal drag; Surface Mass Balance
- Step 2 – Initial Monte Carlo analysis
  - varying most influential parameters from step 1, over extreme (high SLR) min/max range
  - 1 and 2000 partition runs - equal area
- Step 3 – refined Monte Carlo analysis
  - More credible parameter mix/max for next 100 yrs
  - 27 “smart” partitions – designed around drainage basins and climate regions
- Step 4 – scenario driven / time evolved parameter change
  - Future work

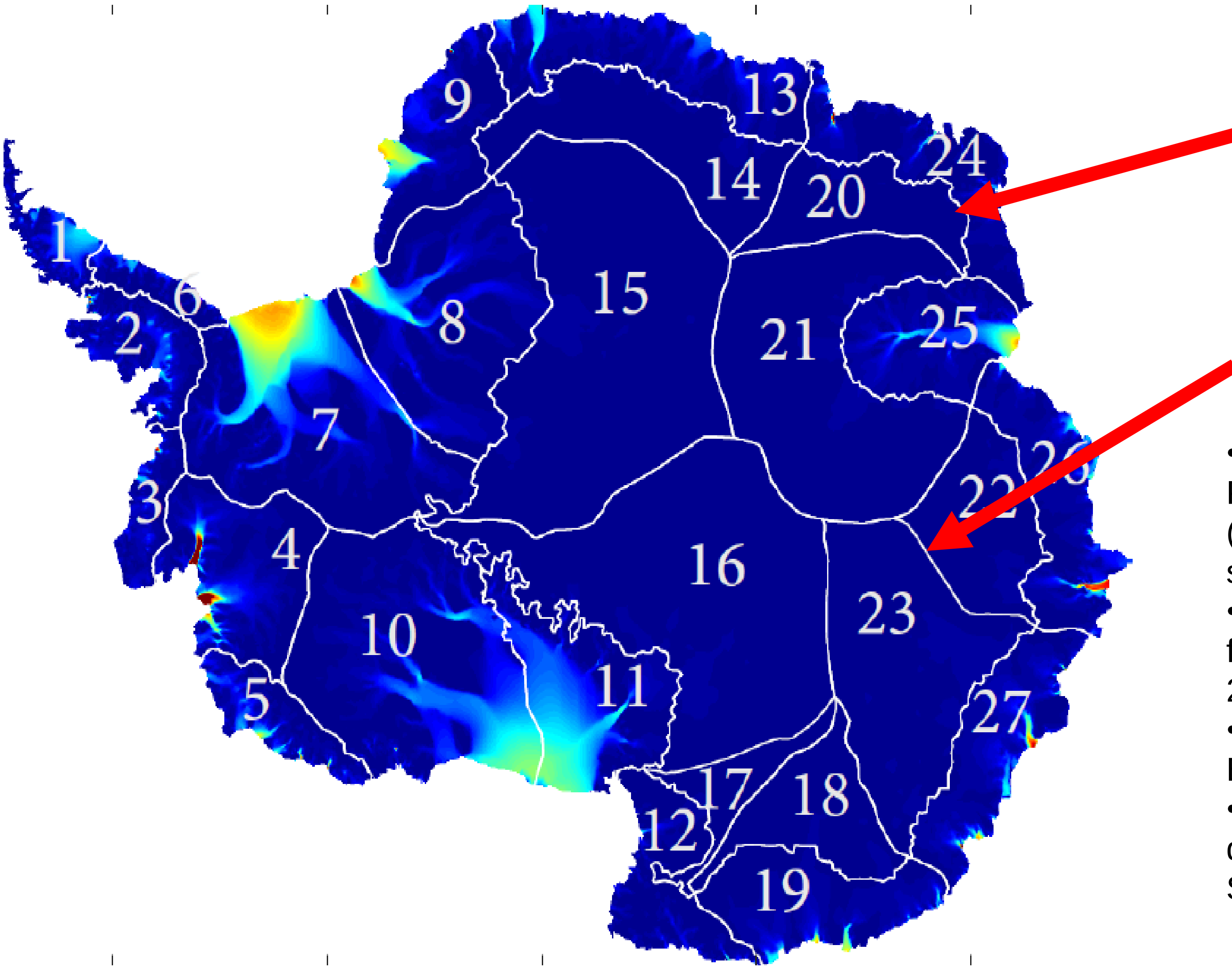
Each AIS UQ Monte-Carlo Experiment: Varied 4 parameters, 200 values each, 800 runs total for each experiment

# Uncertainties in Bedrock Topography

- Bedmap 1 vs Modified Bedmap 2: ~0.4m (~33%) mean SLR difference at 100yrs for extreme climate scenario
- Residual uncertainty in AIS topography is ~ Bedmap1 / Bedmap 2 correction
- **Completing high resolution bedmap of AIS is a quantifiably low risk / high pay-off measurement**



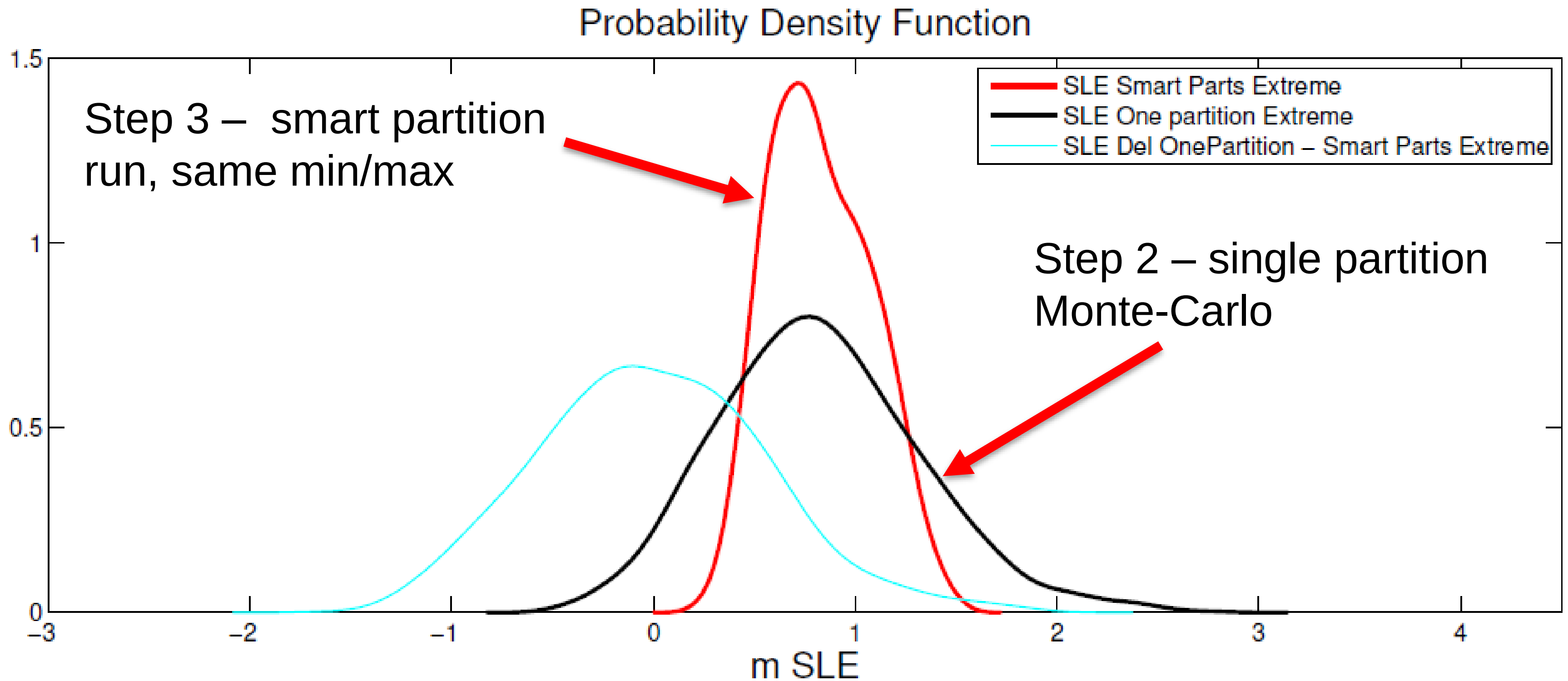
# “Smart” Partitions




- Climate zone - per Palerme et al 2016 (CMIP5 comparison / summary paper)
- Surface melt regions from DeConto et al., 2016
- Drainage basins per Bamber / Rignot / Zwally
- Ocean regions per discussions with M. Schodlok (ECCO2)

# Single Partition vs "Smart" Partitioning

- General effect is **reduction in the spread of sea level contribution** since now not all parts of AIS are assumed to have the same parameter values

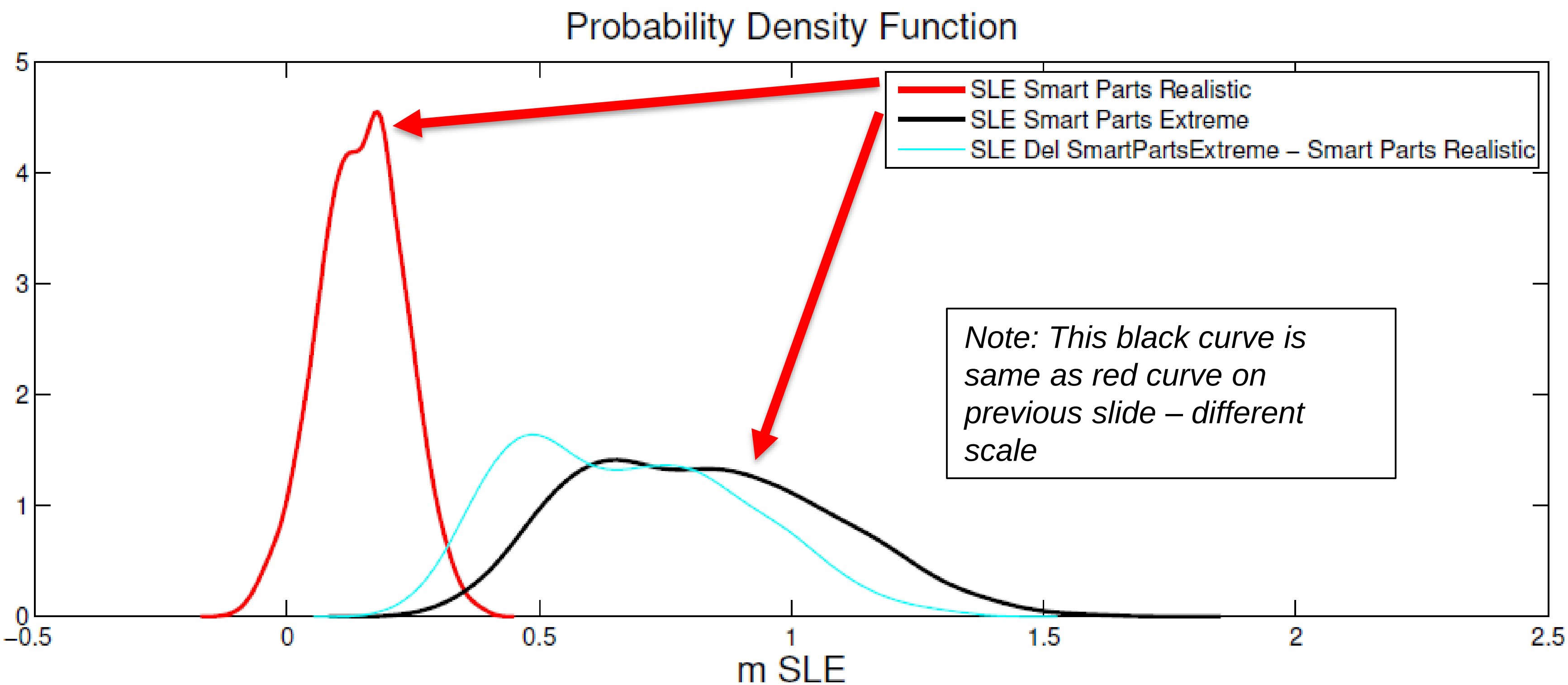


# "realistic" min/max parameter value selection for smart partitions

- All min/max values are **% multipliers** relative to control
- Literature review for **RCP 8.5 climate predicts** for each of the 27 smart partition areas
  - RCP 8.5 regional GCM model predicts used to derive SMB and ice viscosity (based on surface temperature)
    - Minimum +/- on viscosity set to 5% to reflect floor uncertainty value
- Basal drag min/max derived from **range of basal drag inversion solutions** for different model resolutions and optimization levels -> resulted in +/- 15% to +/-25% estimate, region dependent
  - Assumed that over 100 yr time scale our present uncertainty, and not substantial new lubrication / warming, is what drives the range
- Basal (ocean i/f) melt rate – min based on present day mean observation best fit, max based on results of our basal melt sensitivity experiment – multiplied calculated **sensitivity per deg C, by available delta T from CDW** outside each of the cavities
  - Assumes worst case scenario that warmest present day CDW water makes it into ice cavity everywhere around AIS

# Extreme vs More Realistic min/max

- Examples of parameter range differences for “realistic” vs “extreme” runs (% relative to control, which is “best estimate of current conditions”):
- Basal drag: (-15 to -25%) to (+15 to 25%); 0 to -40%
- Viscosity: (-5 to -10%) to +5%; -60% to 0
- Melt rate: 0 to (2x to >200x) ; 0 to 10x



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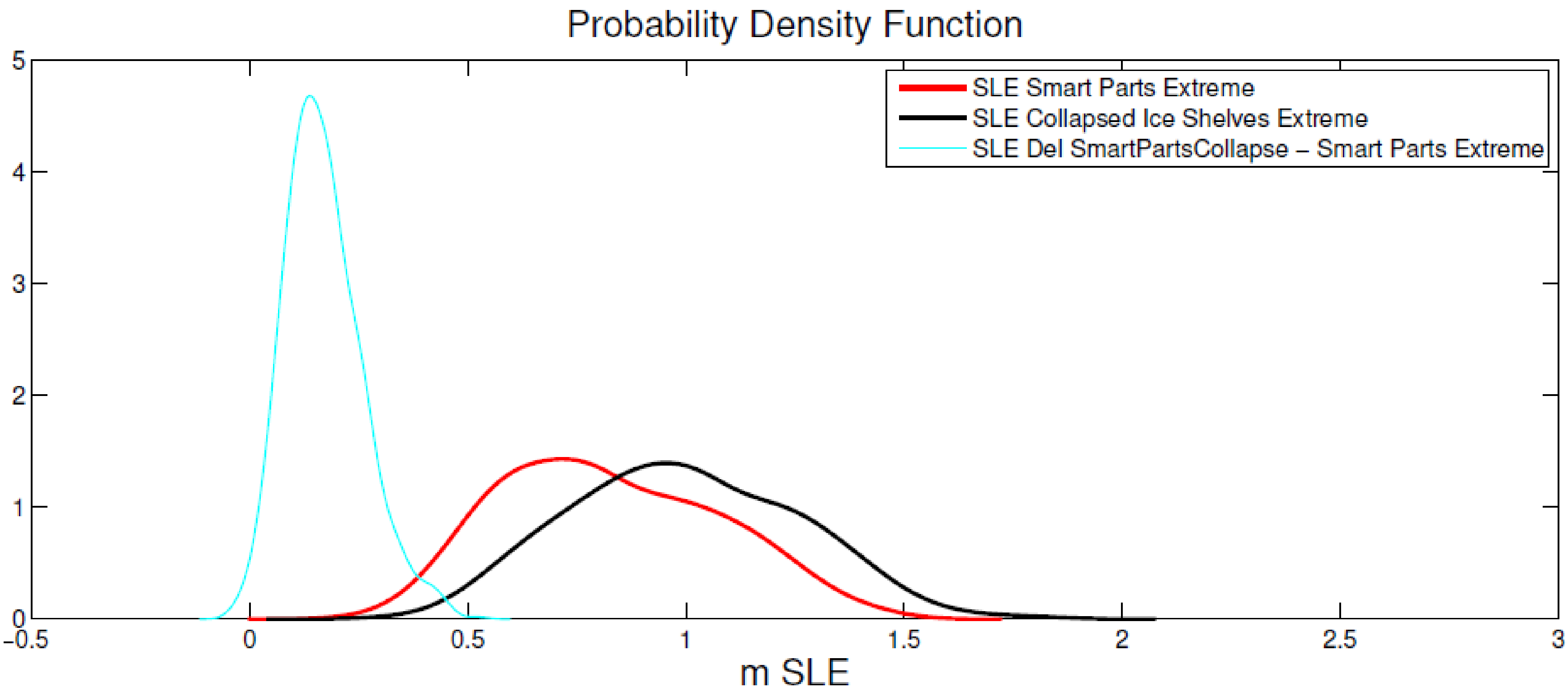
# Impact of Ice Shelf Buttressing

- Experiment to look at 100 yr SLR impact of "instant loss of all AIS ice shelves" (removing backstress)
  - Achieved by new fixed ice shelf at current grounding line. As grounding line retreats, shelf can slowly re-form
  - Max. 95% difference case: ~0.4 m

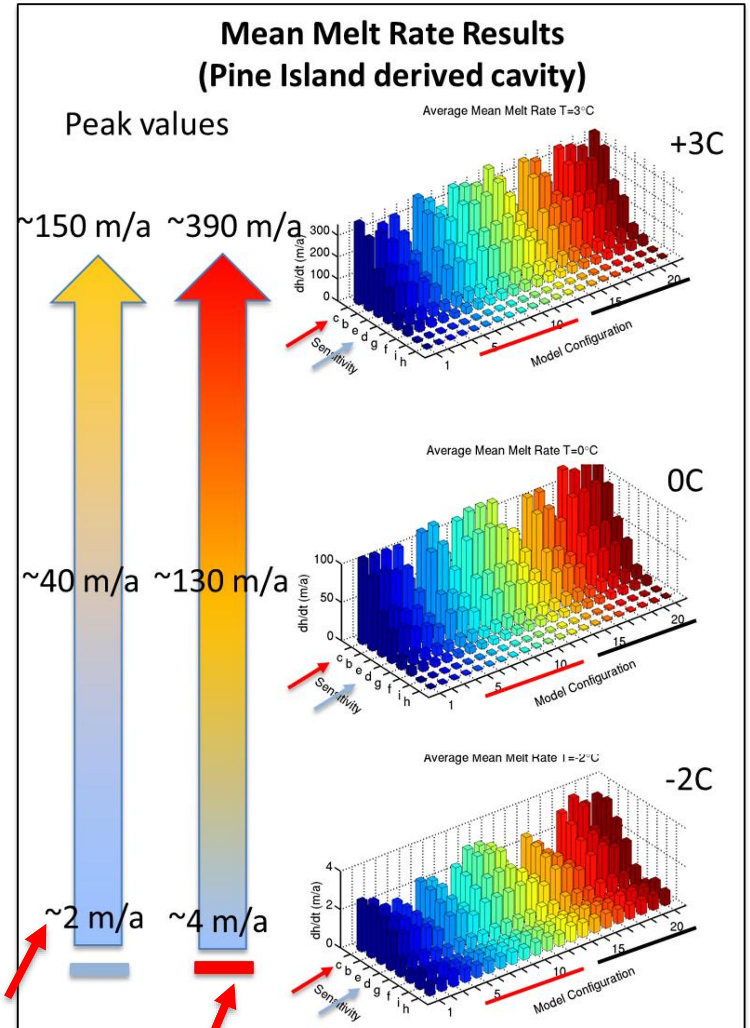


# Basal Melt Rate Sensitivity

**Ocean warming at ice interface potentially important for large SLR cases**

- Ice shelf cavity interface water temperature increase of 2° C can result in 20x to 30x increase in melt rate
  - Credibility / Likelihood of 2° C rise in Southern Ocean ice boundary water in next 100 yrs is very low, but impact is high

- Measurement and prediction of evolution of AIS ice cavity interface water temperature is important for constraining future worst-case SLR




Current best estimate heat exchange coefficients

High end heat exchange coefficients

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# Sea Level Rise Budget Implications

**Pfeffer et al, 2008**
Source for 2m upper bound in NCA. 1.1m of which comes from AIS + GIS

**Table 3.** SLR projections based on kinematic scenarios. Thermal expansion numbers are from (*22*).

| | SLR equivalent (mm) | | |
|---|---|---|---|
| | Low 1 | Low 2 | High 1 |
| *Greenland* | | | |
| Dynamics | 93 | 93 | 467 |
| SMB | 71 | 71 | 71 |
| Greenland total | 165 | 165 | 538 |
| *Antarctica* | | | |
| PIG/Thwaites dynamics | 108 | | 394 |
| Lambert/Amery dynamics | 16 | | 158 |
| Antarctic Peninsula dynamics | 12 | | 59 |
| SMB | 10 | | 10 |
| Antarctica total | 146 | 128 | 619 |
| *Glaciers/ice caps* | | | |
| Dynamics | 94 | | 471 |
| SMB | 80 | | 80 |
| GIC total | 174 | 240 | 551 |
| Thermal expansion | 300 | 300 | 300 |
| Total SLR to 2100 | 785 | 833 | 2008 |

**Likely extreme upper bound** - Our results indicate it is difficult to get this much ice out of GIS, even under extreme conditions

**Reasonable but not extreme upper bound:** Our results agree with there upper bounds given conservative, but not extreme, AIS parameters and boundary conditions. However, if un-expected / extreme conditions develop, AIS is capable of dynamically sourcing substantially more ice in 100 yrs (+1m)

# Conclusions

- Extreme worst-case scenarios show values > 1 m for Antarctica; with “realistic worst case” ~0.25-0.4 m
- Range of sea level PDFs highly dependent on regional dependencies (one vs. “smart” partitions)
- Loss of backstress leads to contribution of <0.5 m (given physics used)
- Early results are useful for identifying some of the most promising new measurements for the sea level rise prediction problem, including
  - Finishing high resolution mapping of AIS bed topography
  - Monitoring heat exchange at AIS ocean / ice interface
- Funding for ice sheet models
  - Proper funding of model development to address missing physics (e.g. ice shelf calving)
  - Computational resources for high resolution Monte Carlo runs


Thank you!

# Picking Updated Worst Case Melt Rates

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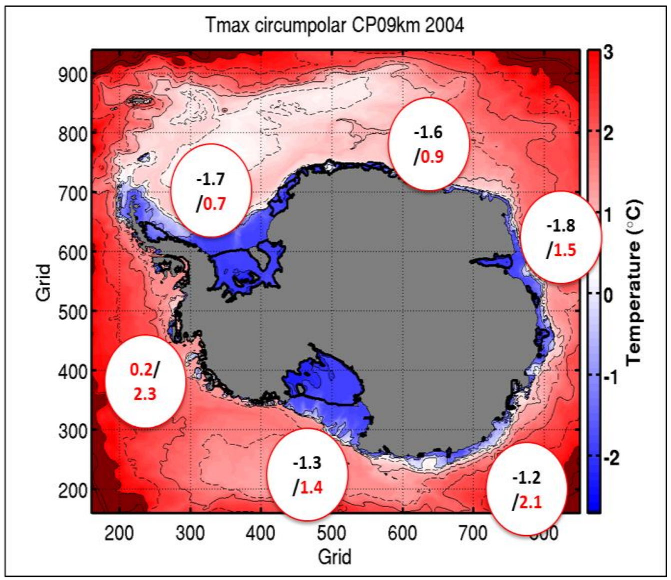
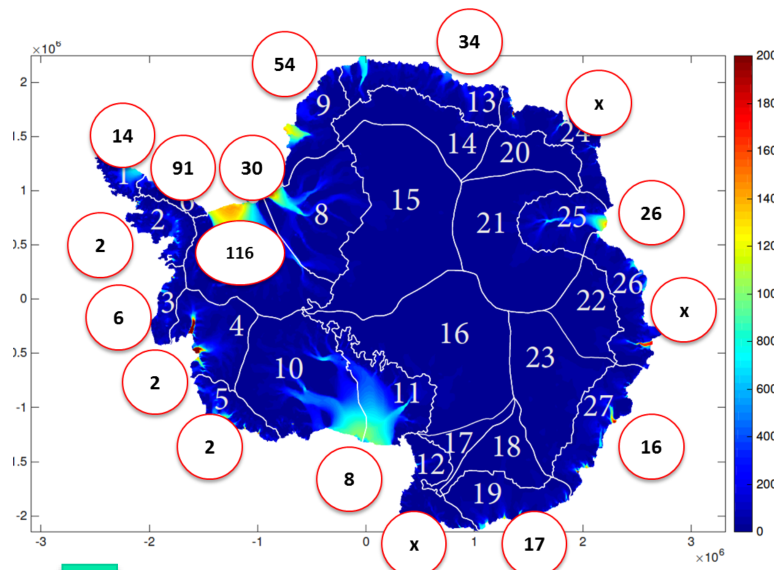
- Melt rate estimates have very large impact on AIS SLR contribution. Extreme melt rates identified model limitation that underestimated AIS mass loss if "choked flow threshold" was exceeded for a glacier
- Using combination of a) ocean / ice sensitivity experiment results (MITgcm) for physically defendable melt rate upper bound, and b) ISSM choked flow sensitivity runs, we selected maximum melt rates for UQ runs which work around known model weakness




Top: cy 2004-2008 mean Temperature maximum in cavity
Bottom: Temperature maximum of Circumpolar Deep Water

Apply cavity specific melt rate to temp sensitivity




Obtain "worst case high melt rate"

Model derived "choked flow limited melt"

For each partition pick the lowest of: "worst case high melt" or "choked flow limited melt"

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# Step 1: Sensitivity analyses

- Individually vary parameters of interest over plausible range and assess impact
  - Basal friction
  - Ice viscosity
  - Surface mass balance
  - Ocean/ice interface melt rate (function of ocean temp and ice cavity geometry)
  - Geographic partitioning (different parts of Antarctica and Greenland behave differently)

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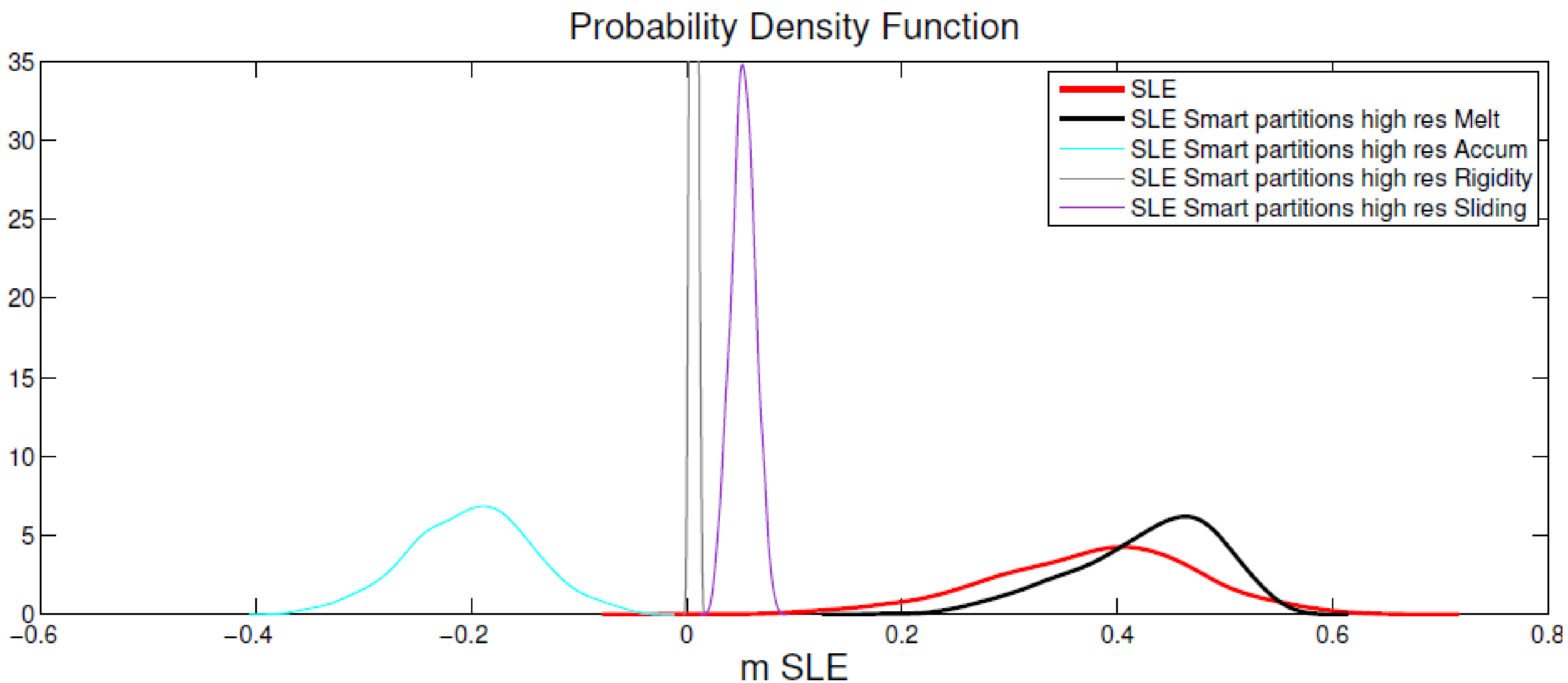
# Step 2: Monte Carlo analyses

- Monte Carlo with random selection of parameters in range (uniform or Gaussian)

- Much computer time
  - AIS: 9-40km grid resolution, multiple physical parameters across 200 values each, randomly sampled, 800 sample experiment
    - State of the art high resolution full continent runs
    - ~100,000 CPU hrs per run, enabled in reasonable calendar time (~1 week) due to parallel implementation of ISSM / Dakota
  - GIS: 1-15km grid resolution, 5 physical parameters across 200 values each, randomly sampled -> 1000 sample experiment

Not sure if we have time for this one



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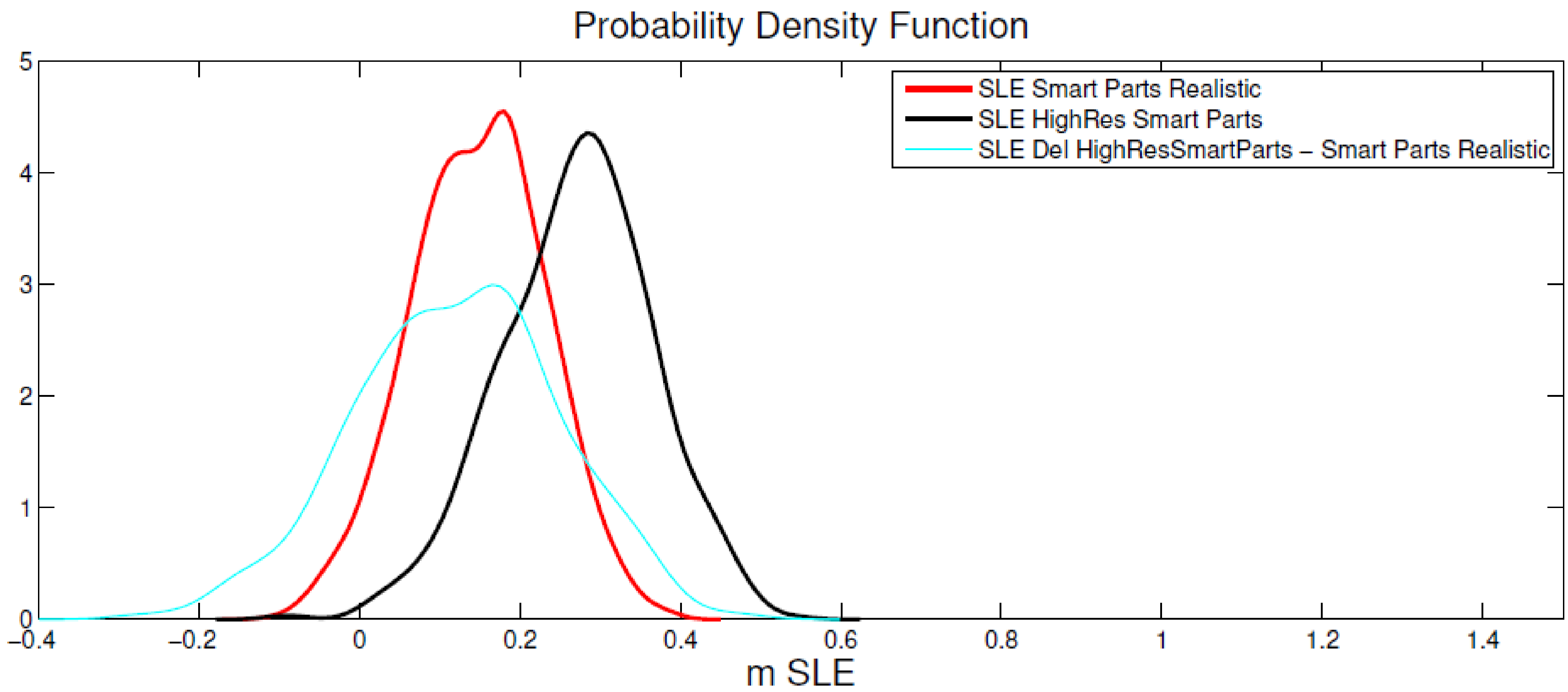

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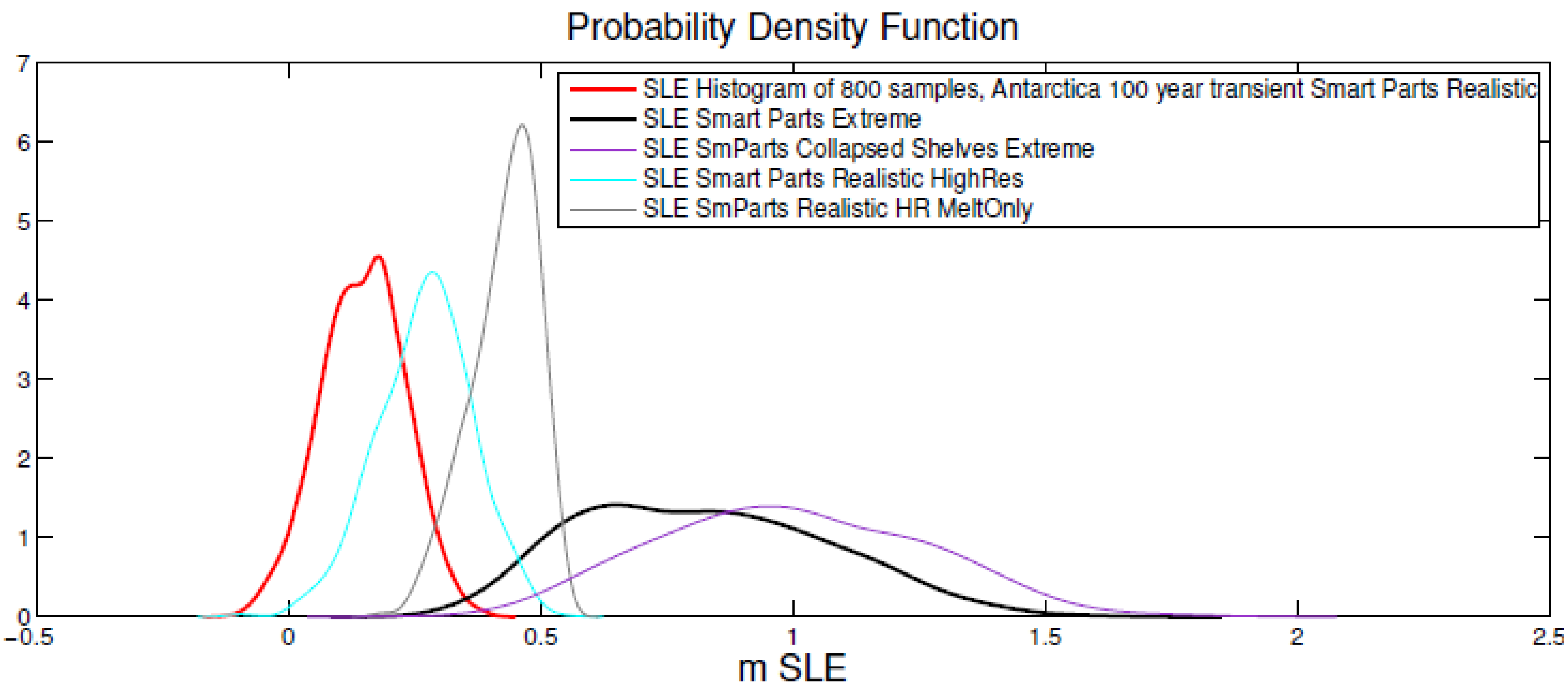

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# A word about model fidelity

- The models we've chosen are state of the art, but to what degree does missing physics hurt us, *particularly* on the tails of the distribution (i.e. large sea level rise) which we especially care about
- To what degree can we use bounding assumptions on parameters to avoid having to get the physics "perfect" yet still get meaningful predictions statistically?
- Constant efforts to quantify errors in current models is important